ELECTROSTATIC PROPULSION USING C_{60} MOLECULES

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ABSTRACT

Buckminsterfullerene, a newly discovered allotrope of carbon (C_{60}), has demonstrated properties that make it an ideal candidate as a propellant for electrostatic propulsion. Here, we present a discussion of the potential benefits C_{60} ion propulsion may provide over conventional ion propulsion and previously suggested methods of cluster ion propulsion. These benefits include improved propulsion system power efficiency, especially in the 1000 to 3000 lbf-s/lbm specific impulse range. This improvement results in part from a decreased power requirement for ionization of the propellant. In addition, because C_{60} is storable, its use will result in a large usable propellant fraction. Finally, the use of C_{60} may relax some engineering constraints, such as cathode discharge current and grid spacing, which restrict the performance of noble gas ion propulsion.

HISTORICAL BACKGROUND

An ideal propellant for ion propulsion has a high molecular mass, a low ionization potential, and a large ionization cross section. These properties help to minimize the energy required to produce each ion which is expelled from the thruster. With propellants of light ion mass, high thruster power efficiencies are achieved only at high acceleration voltages. This produces a high specific impulse, but for a fixed power level (as dictated by the power source) the thrust decreases as the specific impulse increases.

There are applications of electric propulsion, such as orbit transfer missions and North-South station keeping for geosynchronous satellites, in which it is desirable to operate at a low-to-moderate specific impulse (1000 to 3000 lbf-s/lbm). In this range, electric thrusters with conventional propellants such as xenon become less efficient as shown in Figure 1.

Thus, a gap in propulsion capability exists for missions with a requirement for low-to-moderate specific impulse, yet at higher propulsion system efficiency than is provided by state-of-the-art xenon ion engines or arcjets.

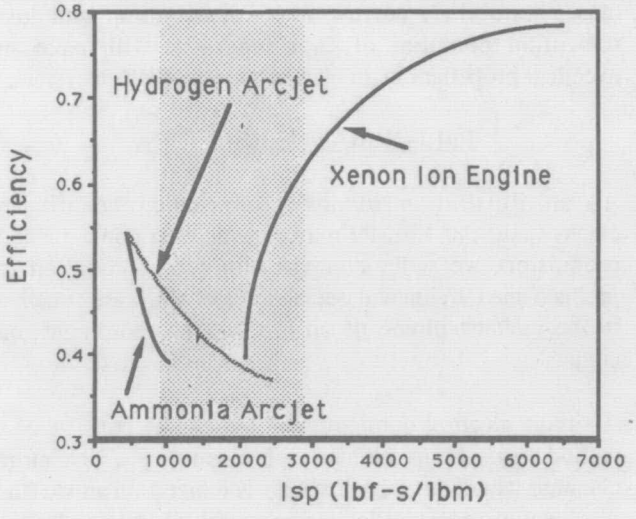

Figure 1. - Efficiencies of xenon ion engine, hydrogen arcjet, and ammonia arcjet as a function of specific impulse. Data are experimental.[1,2] Shaded region shows where thruster performance falls below 60 percent.

In an effort to fill this gap in propulsion capability, researchers have investigated the production of clusters bound by van der Waals forces. However, the performance of cluster ion engines depends on considerations such as high clustering efficiency and the production of clusters with a narrow charge-to-mass ratio distribution. Early attempts at developing cluster ion engines met with difficulty in achieving high (greater than 70 percent [3]) clustering efficiency and narrow cluster mass distributions. In addition, van der Waals clusters are fragile (the binding energies per atom are tenths of an electron-volt), making them susceptible to fragmentation during ionization.[4]

In 1984, Rohlfing generated clusters of carbon atoms, C_n for n=1-190.[5] He noted that clusters of 60 carbon atoms occurred most frequently for molecules composed of more than 40 atoms. By adjusting the vaporization conditions, this peak in the mass spectrum could be made even more

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pronounced. One year later, Kroto suggested the now well known structure of the C_{60} molecule.[6] The structure is like that of a geodesic dome with a carbon atom at each vertex. The molecule has been named buckminsterfullerene after the inventor of the geodesic dome, Buckminster Fuller. Kratschmer and Whetten have investigated the formation of C_{60} from the vaporization of graphite and have demonstrated methods of producing and separating macroscopic quantities of various fullerenes. [7,8,9]

C_{60}, with a molecular mass of 720 amu, has proven to be extremely stable, can be easily produced, and is electrically insulating when deposited. Further, only a small incidence of fragmentation of diatomic carbon from the molecule has been observed during ionization[9]. The ionization potential of C_{60} is about 7.5 eV, well below the 12.12 eV necessary to ionize xenon. The double ionization potential of C_{60} is approximately 16 eV. The ruggedness, large mass, storability, narrow mass distribution, and low ionization potential of C_{60} suggest it will make an excellent propellant in an electrostatic propulsion system.

PERFORMANCE BENEFITS

As an illustration of the performance benefit an electrostatic C_{60} thruster may provide over noble gas ion propulsion, we will compare the energy required to produce one C_{60} ion and one xenon ion which are expelled in the exhaust plume of an electron bombardment ion engine.

A simple electron bombardment ion engine consists of a cathode for the production of electrons, a discharge chamber where the propellant gas is ionized, an anode (the discharge chamber walls), a screen grid, and an accelerator grid. Brophy has derived an expression for the average energy required to produce an ion expelled in the exhaust plume: [10]

$$\varepsilon_B = \frac{\varepsilon_p^*}{f_B[1-e^{-C_0 m (1-n_\mu)}]} + \frac{f_C V_D}{f_B} \qquad (1)$$

where f_B is the fraction of ions extracted from the plasma in the discharge chamber, f_C is the fraction of ion current to the cathode surfaces, V_D is the discharge (anode) voltage, C_0 is the primary electron utilization factor, m is the propellant flow rate, and n_μ is the propellant utilization efficiency. The factor ε_p^* is called the baseline plasma ion energy cost, and is defined as:

$$\varepsilon_p^* = \frac{\varepsilon_0 + \varepsilon_M}{1 - \frac{V_C+\varepsilon_M}{V_D}} \qquad (2)$$

where ε_0 is the average energy lost to ionization and excitation, ε_M is the average energy of Maxwellian electrons reaching the anode, and V_C is the plasma potential from which electrons emitted at the cathode are accelerated. The ion energy cost is an important figure of merit for an ion propulsion system because energy which is used to create ions can not be recovered. Hence, it plays an important role in determining the efficiency of an electric propulsion system.

C_0, the primary electron utilization factor, reflects the degree of interaction between neutral particles and primary electrons (i.e. those electrons emitted by the cathode which have not yet undergone a collision). Large values of C_0 are desirable because they reflect more efficient ion production. From kinetic theory, one can show that C_0 is proportional to the total collision cross section and inversely proportional to the velocity of the neutral propellant particles. Assuming a fixed temperature, the velocity of the neutral particles is:

$$V = \sqrt{\frac{2K_BT}{\pi M}} \qquad (3)$$

where T is the temperature, K_B is Boltzmann's constant, and M is the mass of the particle. The ratio of the velocities of C_{60} molecules to xenon atoms is 0.43. If we assume that the collision cross section is proportional to the square of the neutral particle radius, then we find that the collision cross section of C_{60} is approximately 2.5 times that of xenon where the radius of a xenon atom is approximately 2.2 A, and the radius of a C_{60} molecule is approximately 3.5 A. Hence, C_{60}'s primary electron utilization factor is expected to be about 6 times that of xenon.

An accurate estimate of ε_p^* for the two propellants would require a knowledge of various collision cross sections of C_{60}, the average energy of the Maxwellian electrons leaving the plasma at the anode, and the plasma potential from which electrons emitted at the cathode are accelerated. Qualitatively, we expect ε_p^* to be less for C_{60} than for xenon because the ionization potential of C_{60} is lower than xenon, and therefore the discharge voltage for C_{60} need not be as high. These factors will contribute to lower values of ε_0, ε_M and V_D. Using typical values of the above variables for xenon of m = 1000 mA eq., $f_B = 0.6$, $f_C = 0.1$, $V_D = 50$ V, $C_0 = 3.0$ A eq.$^{-1}$, and $\varepsilon_p^* = 50$ eV, we find an energy cost per xenon beam ion of approximately 190 eV for a propellant utilization efficiency of 0.8. If we approximate the energy cost per C_{60} ion using the primary electron utilization factor calculated above, we find a cost of 90 eV for the same propellant utilization efficiency. However, one would expect the utilization efficiency of a heavy propellant such as C_{60} to be higher than that of xenon because of the lower diffusivity of the molecules. After dividing the energy cost per ion by the ion masses, we see that the

energy cost per atomic mass unit (amu) for C_{60} molecules is only 8.6 percent of that required for xenon.

In the above calculations we have neglected the thermal energy carried away by the C_{60} molecules resulting from sublimation. However, an upper limit to the amount of thermal energy the C_{60} molecules may contain is evident from statistical mechanics:

$$\varepsilon_T = (3n - 6)\, K_B T \qquad (4)$$

where ε_T is the thermal energy and n is the number of atoms in the molecule. For C_{60} molecules at a sublimation temperature of 350 degrees centigrade, this energy would be less than 9.4 eV, or about 10 percent of the total energy cost per ion.

We can see the improved engine efficiency at low specific impulse by studying the relation:

$$\eta = \frac{\gamma^2 \eta_\mu}{1 + \frac{2e}{m_i}\left(\frac{\gamma\, \eta_\mu}{g\, I_{sp}}\right)^2 (\varepsilon_B + V_{nc})} \qquad (5)$$

where γ is the thrust loss factor due to beam divergence and double ionization, η_μ is the propellant utilization efficiency, m_i is the ion mass, Isp is the specific impulse, and Vnc is the neutralizer coupling voltage. For a xenon ion engine operating at 1500 lbf-s/lbm and an ion production cost of 190 eV per ion, the efficiency would be approximately 40 percent. However, because of the higher accelerating voltage (and therefore beam voltage) and lower ion production cost, a C_{60} ion engine has a calculated efficiency of about 67 percent for the same specific impulse of 1500 lbf-s/lbm. Thus, the improvement in efficiency at low specific impulse is evident. A comparison between the efficiency of a xenon ion engine and a C_{60} thruster over the specific impulse range of 1000 to 3000 lbf-s/lbm is displayed in figure 2.

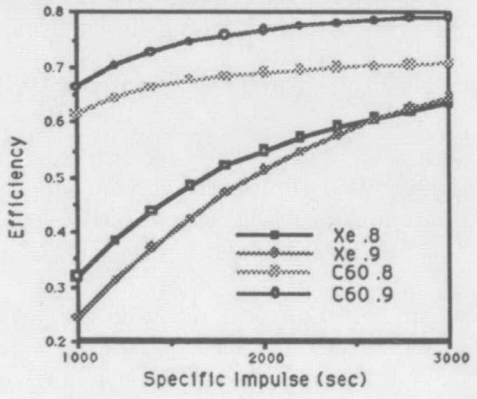

Figure 2. - Theoretical efficiencies of xenon ion engine and C_{60} thruster as a function of specific impulse for two different propellant utilization efficiencies.

In addition to improvements in the thruster power efficiency, the use of C_{60} molecules may result in increased thruster lifetime. Preliminary studies at UCLA in which C_{60} ions were accelerated to velocities of 6700 m/s into stainless steel and silicon barriers have provided no evidence of sputtering of these surfaces.[11] Instead, the fullerenes merely "bounce back" without depositing energy in the surface of the material. Also, because heavy ion propellants such as C_{60} have charge to mass ratios much smaller than that of atomic propellants, lower discharge currents are required to achieve the same mass flux through the accelerator grids. This fact may result in improved thruster lifetime because of reduced demands on the cathode.

THRUSTER DESIGN

A simple C_{60} electrostatic thruster would include a discharge chamber with a cathode, anode, weak magnetic field generated by external windings, propellant inlet, and screen and accelerator grids. A sublimation chamber would be attached to the back of the discharge chamber, separated by a fine mesh through which sublimated C_{60} molecules would diffuse. The C_{60} molecules would then be ionized through the use of a DC discharge. The use of RF radiation in the discharge chamber is another possible ionization scheme. C_{60} does have the tendency to plate materials with which it comes in contact. However, it is not electrically conducting. This property makes the RF method of ionization attractive. Another propulsion scheme is to alternately accelerate negative and positive C_{60} ions. The use of negative C_{60} ions may prove very efficient because of the high electron affinity of C_{60}.

CONCLUSION

Heavy ion propulsion has been investigated since the 1960's in an effort to achieve higher performance from an electrostatic accelerator than that which is possible with atomic propellants. The recent discovery of C_{60} and some of its properties may be a breakthrough in the area of heavy ion propulsion.

ACKNOWLEDGEMENT

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